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An Examination of Heart Rate Variability at Anaerobic Threshold and Respiratory Compensation Points During Cardiopulmonary Exercise Test

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Research Article
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Abstract

The aim of this study is to examine the changes in HRV values before, during (at AT and RC) and after maximal incremental cardiopulmonary exercise test. The sample comprised 121 healthy men who recreational do exercise 2-3 days a week. (age: 30.5 ± 4.6 years, height: 177.8 ± 6.1 cm; weight: 80.2 ± 10.2 kg). Anthropometric measurements were measured by using body analyzer, and aerobic capacities of participants were measured by using the cardiopulmonary exercise test via the Bruce protocol. According to this, heart rate variability recordings were taken at seven stages during the cardiopulmonary exercise test: before the test (1), at the beginning of the test (2), between the beginning of the test and the anaerobic threshold (3), at the anaerobic threshold (4), between the anaerobic threshold and the respiratory threshold (5), at the respiratory threshold (6), and finally (7), 30 seconds after the cardiopulmonary exercise test. Repeated measures analysis of variance (ANOVA) was used to compare the HRV values obtained from the test stages. In conclusion, using a gas analyzer during cardiovascular exercise testing, HRV values (MeanRR, SDNN, RMSSD, LFnu) determined at seven stages continue to decrease from the beginning. A rest period of 30 seconds (passive rest) immediately after completing the exercise does not seem to be sufficient for recovery. According to the results of this study, it can be considered that the sympathetic nervous system activity (LFnu) exhibits a more pronounced appearance at threshold zones.
Keywords: Autonomic nervous system, Aerobic capacity. Heart rate variability.

Kardiyopulmoner Egzersiz Testi Sırasında Anaerobik Eşik ve Solunum Kompenzasyonunun Kalp Atım Hızı Değişkenliği Açısından İncelenmesi

Öz

Bu çalışmanın amacı, maksimal artan kardiyo-pulmoner egzersiz testi öncesi, sırasında (AT ve RC'de) ve sonrasında HRV değerlerindeki değişiklikleri incelemektir. Örneklem, haftada 2-3 gün rekreaktif olarak egzersiz yapan 121 sağlıklı erkekten oluştu (Yaş 30,5 ± 4,6 yıl; Boy 177,8 ± 6,1 cm; Ağırlık 80,2 ± 10,2 kg). Antropometrik ölçümler vücut analiz cihazı kullanılarak, aerobik kapasiteleri Bruce protokolü kullanılarak kardiyo-pulmoner egzersiz testi ile ölçüldü. Buna göre kardiyo-pulmoner egzersiz testi öncesinde (1), test başlangıcında (2), test başlangıcı ile anaerobik eşik arasında (3), anaerobik eşikte (4), anaerobik eşik ile solunum eşiği arasında (5), solunum eşiğinde (6) ve son olarak kardiyo-pulmoner egzersiz testi sonrasında (7) 30'ar saniye olmak üzere yedi aşamada kalp hızı değişkenliği kayıtları alındı. Test aşamalarından elde edilen HRV değerlerini karşılaştırmak için tekrarlı ölçümler varyans analizi (ANOVA) kullanıldı. Sonuç olarak, kardiyovasküler egzersiz testi sırasında gaz analizörü kullanılarak yedi aşamada belirlenen HRV değerleri (MeanRR, SDNN, RMSSD, LFnu) başlangıçtan itibaren azalmaya devam etmektedir. Egzersizi tamamladıktan hemen sonra 30 saniyelik bir dinlenme süresi (pasif dinlenme) toparlanma için yeterli görünmemektedir. Bu çalışmanın sonuçlarına göre sempatik sinir sistemi aktivitesinin (LFnu) eşik bölgelerinde daha belirgin bir görünüm sergilediği düşünülebilir.
Anahtar Kelimeler: Otonom sinir sistemi, Aerobik kapasite, Kalp atım hızı değişkenliği.

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INTRODUCTION

How the heart works is not a metronome, times differ between both heartbeats, and this is called heart-rate variability (HRV) (McCraty and Shaffer, 2015; Poehling, 2019). During physical exercise, sympathetic activity increases, and parasympathetic activity balances with the autonomic nervous system (ANS) (Alparslan et al., 2020; Poehling, 2019; Sanz-Quinto et al., 2018). Long-term measurements (more than 24 hours) are recommended for HRV, but some studies have shown consistent results in short-term (up to 5 minutes) and ultra-short-term (up to 30 seconds) measurements too (Shaffer and Ginsberg, 2017; Xhyheri et al., 2012). Of course, shorter time measurements will be used to use HRV in exercise. Although HRV has been observed mostly during rest (Baek et al., 2015; Fortes et al., 2017), it is now the subject of research especially in recovery after exercise (Esco et al., 2016; Morales et al., 2014; Williams et al., 2018). Previous studies have also utilized HRV during exercise and evaluated the results (Arabacı et al., 2020; Giles and Draper, 2018; Lewis et al., 2007; Simões et al., 2016).

The gold standard for the test, which is accepted as the determinant of aerobic capacity, is the cardiovascular endurance running tests using a gas analyzer (Poole and Jones, 2017). During the cardiopulmonary exercise test (CET), anaerobic threshold (AT) and respiratory compensation (RC) points can also be determined. It is wondered how HRV changes occur before, during and immediately after this test, which can be regarded as a high-intensity test, near the maximum heart rate (220-age), and during the test (Jamnick et al., 2018).

We have encountered studies before during the CET which (Poehling, 2019) investigated the effect of maximal and submaximal exercise on HRV (Guilkey et al., 2015). Additionally, there are other empirical studies that investigated the self-regulatory effect of parasympathetic modulation in maximal and submaximal exercises in girls and boys (Lewis et al., 2007) and monitored the state of HRV with increasing intensity in cycling tests (Hautala et al., 2003).

However, we could not find any study related to the observation of HRV values at AT and RC during CET in a laboratory environment. More specifically, these threshold points are important indicators used in training planning for athletes and coaches. Therefore, the current study aimed to shed light on how HRV changes occur before, during and after the CET especially at the AT and RC during the CET. We hypothesized that HRV values would differ in each CET step of active participants.

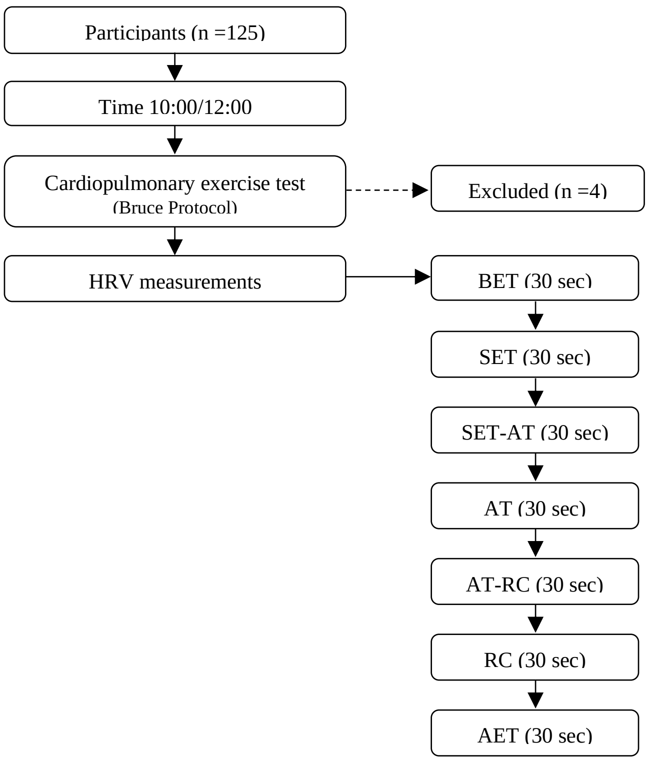
MATERIAL AND METHODS

Participants

One hundred twenty-five healthy men were recruited on a voluntary basis. Four of the participants were excluded from the current study because they did not complete the test. The final sample comprised one hundred twenty-one individuals (age: 30.5 ± 4.6 years, height: 177.8 ± 6.1 cm; weight: 80.2 ± 10.2 kg). Participants completed the International Physical Activity Questionnaire-Short Form (IPAQ-SF) before the CET. Based on the results obtained from the IPAQ-SF, participants self-reported physical activity level was 14.3% high, 43.7% medium and, 42.0% low in the current study. According to IPAQ, the current sample claimed that they participate physical exercise 2-3 days a week at a recreational level. Participants were reported to have experienced no injury or injury prior to the experiments. Participants signed an informed consent form.

Study Design

Participants' tests were conducted on weekdays (ie, between 10:00 and 12:00). Measurements were made in a laboratory at 22-24 °C and 33-45% humidity. Before the test, the participants were warned not to engage in heavy physical activity and not to consume anything such as food, medicine, coffee two hours before the test. The tests were carried out in groups of 8 people on 15 non-consecutive days. Body compositions of participants were measured by undermentioned body analyze devices. According to this, heart rate variability recordings were taken at seven stages during the cardiopulmonary exercise test: before the test (1), at the beginning of the test (2), between the beginning of the test and the anaerobic threshold (3), at the anaerobic threshold (4), between the anaerobic threshold and the respiratory threshold (5), at the respiratory threshold (6), and finally (7), 30 seconds after the cardiopulmonary exercise test. The test schedule and HRV parts of the test applied to the participants are shown in Figure 1.



BET=Before Exercise Test, SET= Start Exercise Test, AT=Anaerobic Threshold, RC=Respiratory compensation, AET=After Exercise Test

Figure 1. Study design

Measurements

Body composition: The height was measured with a 1/10 cm sensitivity (Holtein Harpenden 601, Holtain Ltd., UK). Body weight and Body Mass Index (BMI) values of the participants (InBody 270, Biospace Co., S. Korea) were determined with a bioelectrical impedance device. Measurements were made according to the procedure in the device's manual.

Aerobic capacity: For the test, a gas analyzer treadmill, which is accepted as the gold standard, was used to determine the maximal oxygen consumption (h/p/cosmos quasar med 170-190/65, h/p/cosmos and medical GMBH, Germany). The Bruce protocol was performed. The staged protocol began at 1.7 mph at 10% grade with increasing work rate (speed and grade) every 3 minutes until VO_{2max} was reached. Expired gas fractions (oxygen and carbon dioxide) were collected at the mouth and analyzed with a metabolic cart (Cosmed Quark CPED metabolic cart, Roma, IT). Measurements were processed in Omnia - Standalone software for Microsoft Windows version 1.4. The criteria for VO_{2max} were predetermined as 2 of the following: if there was a plateau in oxygen consumption despite an increased work (± 2 $ml.kg^{-1}.min^{-1}$); the respiratory exchange ratio of >1.10; and a heart rate within ten beats of age-predicted maximum (220-age). Bruce protocol was applied after 10 minutes warm-up period. In determining the VO_{2max}, the analysis of the data was carried out by taking the average values at 15-second time intervals. On the other hand, in the threshold calculations, a new data group created by taking the average values of the data for 5 seconds was used. The anaerobic threshold is a point during exercise where the body transitions from aerobic metabolism to anaerobic metabolism, representing an intensity of exercise. The respiratory threshold is a point during exercise where the body's respiratory system capacity is exceeded and respiration accelerates. The Bruce protocol is a protocol that gradually increases exercise intensity over time, so gas analysis data is recorded at each stage of exercise at a specific duration and speed, and changes in respiratory gases are examined based on exercise intensity Gas analysis data typically includes parameters such as oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory rate (RR), and tidal volume (VT). Exercise stages and gas analysis data in the Bruce protocol are recorded in graphs and tables for later analysis. Threshold values such as anaerobic threshold and respiratory threshold can be correlated with gas analysis data such as VO_2, VCO_2, RR, and VT (Ekkekakis et al., 2008). The determination of anaerobic threshold and respiratory threshold; Expired gas fractions (oxygen and carbon dioxide) were collected at the mouth and analyzed with Cosmed Quark CPED metabolic measurement device. Measurements were processed in Omnia - Standalone software for Microsoft Windows version 1.4, and threshold points were marked by the device and the program.

Heart rate variability: Polar H7 band was used to detect heart rate (Polar Electro, Kempele, Finland). Heart rate was converted into HRV data with the Elite HRV program. Detailed analyzes were performed using the Kubios HRV program version 3.3.1 (Biosignal Analysis and Medical Imaging Group, Finland, version 3.1.0.1) (Tarvainen et al., 2014). A sampling rate of 1000 Hz was chosen, and recordings were transferred to a PC via e-mail. Before the exercise test, each subject was instructed to lie on the exercise mat in a dimly controlled climate-controlled laboratory for 10 minutes following the recommendations adopted (Marek et. al, 1996). The spectral response provided by the system was broken down into 3 bands: very low frequency (0.003–0.04 Hz), low frequency (0.04–0.15 Hz), and high frequency (0.15–0.4 Hz). HRV parameters used in the research: "MeanRR: Mean of R-R intervals in milliseconds, SDNN: Standard deviation of NN intervals, RMSSD: Root mean square of successive RR interval differences, LFnu power: Normalized absolute power of the low-frequency band (0.04–0.15 Hz), HFnu power: Normalized relative power of the high-frequency band (0.15–0.4 Hz), LF/HF: Ratio of LF-to-HF power" (Shaffer and Ginsberg, 2017).

Research Ethics: The study was approved by the Osmangazi University research ethics committee (Approved date 27.02.2020 and number 2019-89).

Data Analysis

The mean and standard deviation were calculated. Sample size was calculated by using G*power program (Ver.3.1.9.6). Repeated measures analysis of variance (ANOVA) was used BET-SET-AT-RC-AET. Bonferroni test was used for intra-group comparisons. Eta-squared (η^2) is a measure of effect size for use in ANOVA. All calculations were made with SPSS version 22, statistical software (SPSS Inc., Chicago, IL, USA), and the level of significance was set at $p<0.05$.

FINDINGS

Physical characteristics and VO_{2max} mean values of the participants are given in Table 1. The comparison of HRV values recorded for BET, SET, SET-AT, AT, AT-RC, RC, and AET sections is shown in Figure 2.

Table 1. Physical characteristics of the subjects (n = 121)

Physical Characteristics	Mean	±	SD	Max.	Min.
Age (years)	30.5	±	4.6	38	22
Height (cm)	177.8	±	6.1	192.1	160
Weight (kg)	80.2	±	10.2	110.0	55.6
BMI ($kg.m^{-2}$)	25.3	±	3.1	33.7	16.3
Body fat (%)	20.3	±	5.6	35.7	8.7
VO_{2max} ($ml.kg^{-1}.min^{-1}$)	38.7	±	4.1	50.5	30.5
AT VO_2 ($ml.kg^{-1}.min^{-1}$)	27,6	±	9.0	50.3	15.3
RC VO_2 ($ml.kg^{-1}.min^{-1}$)	36.2	±	5.4	49.4	21.8

Figure 2 shows the comparison of HRV values recorded seven different stages. In intra-group comparisons, stages were evaluated by comparing them with the next. There was a significant difference in MeanRR, the HRV measure, among the various stages (F=671.9***, η^2=0.87, p<0.001). While there was a significant difference in SDNN, another HRV measure, for repeated measurements (F=135.7***, η^2=0.59, p<0.001), there were significant intra-group differences for BET *vs.* SET, SET *vs.* SET-AT, and SET-AT *vs.* AT (p<0.001). HRV changes for AT *vs.* AT-RC (p=0.10) and AT-RC *vs.* RC (p=1.00) were not statistically significant. There was a significant difference in RMSSD, another HRV variable, for repeated measurements

(F=27.96***, η^2=0.23, p<0.001), and significant intra-group differences were observed for BET *vs.* SET (p<0.001) and SET *vs.* SET-AT (p<0.001) comparisons. However, there were no statistically significant intra-group differences for SET-AT *vs.* AT, AT *vs.* AT-RC, and AT-RC *vs.* RC (p=1.00).

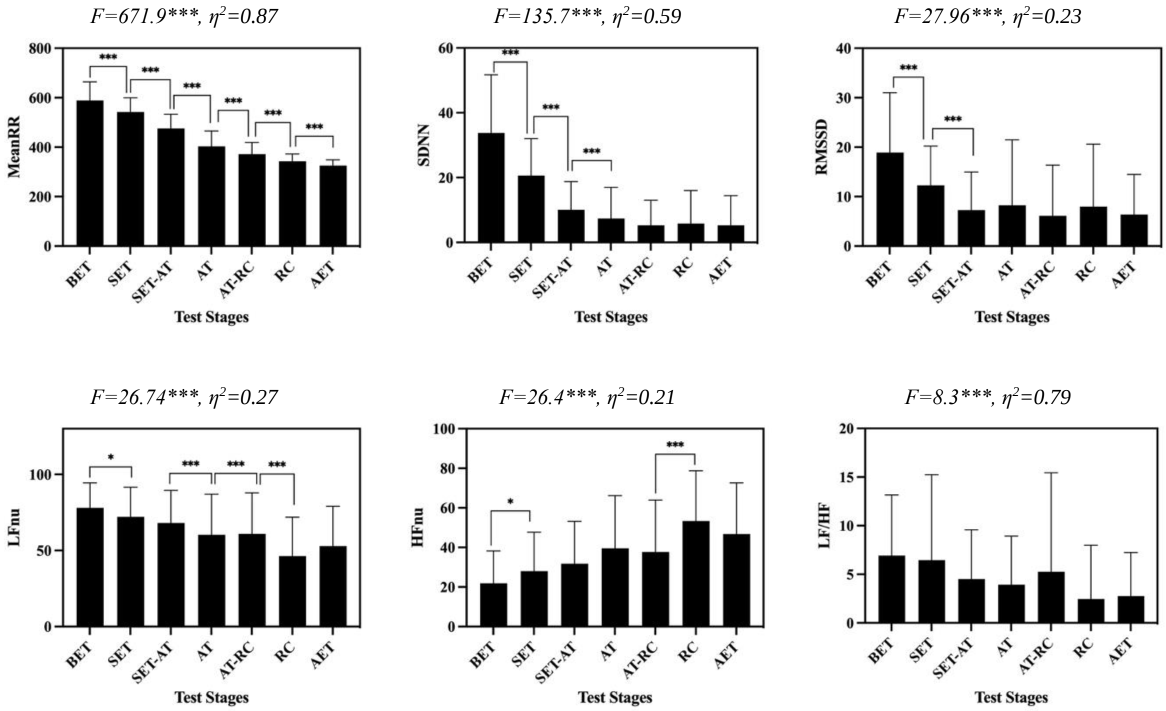


Figure 2. The comparison of HRV values recorded BET, SET, SET-AT, AT, AT-RC, RC, and AET

For frequency-domain measurements, there was a significant change in LF for repeated measurements (F=26.74***, η^2=0.27, p<0.001). Intra-group differences were also significant for BET *vs.* SET (p<0.05) and SET-AT *vs.* AT, AT *vs.* AT-RC, and AT-RC *vs.* RC comparisons (p<0.001). There was a significant result for repeated measurements of HF (F=26.4***, η^2=0.21, p<0.001). Intra-group differences were also significant for BET *vs.* SET (p<0.05) and AT-RC *vs.* RC (p<0.001) comparisons. There was no significant difference between SET *vs.* SET-AT (p=1.00), AT *vs.* AT-RC (p=0.18), and AT-RC *vs.* RC (p=1.00) comparisons. There was a significant difference in LF/HF (F=8.3***, η^2=0.79, p<0.001) for repeated measurements.

DISCUSSION

The aim of this study was to examine changes in HRV values before, at start, at threshold regions (AT and RC), and after maximal incremental cardiopulmonary exercise testing. Short and ultra-short-term HRV measurements have been previously conducted during increased intensity maximum tests (Baek et al., 2015; Esco and Flatt, 2014; Nakamura et al., 2015; Altini et al., 2017; Neufeld et al., 2019). Among these results, empirical evidence on RC and HRV values are also available (Cottin et al., 2007; Tulppo et al., 1998; Yamamoto et al., 1991). The results of the above studies and our results are generally consistent in terms of HRV changes. To the best of our knowledge, in presented study HRV changes were evaluated collectively for the first time in the laboratory settings using the Bruce protocol in healthy men before, during and after the CET. Main findings of the research, MeanRR, SDNN, RMSSD, and LFnu values measured before the test and higher continued to decrease as the test phase became more difficult. It has previously been shown that when RR interval decreases during an incremental exercise, total HRV decreases (Cottin et al., 2007; Tulppo et al., 1998; Yamamoto et al., 1991). Our results provide support for this notion that HRV decreases during incremental performance. This can be explained by the marked change in autonomic function by sympathetic activation after a gradual vagal retraction for exercise reasons (Dourado et al., 2010).

Previous studies shown the intensities in AT and RC are highly compelling and create significant autonomic responses. (Cassirame et al., 2015; Chwalbinska-Moneta et al., 1989). Ramos-Campo et.al. (2017) investigation where 24 professional basketball players used HRV values to evaluate their respiratory thresholds, there was a significant correlation between HRV and gas methods, among the methods they used to determine respiratory thresholds. They stated that HRV can be used to determine the respiratory threshold, and this is a practical and inexpensive method compared to the laboratory environment. Karapetian et al., (2008) found a strong significant correlation (r=0.89) between oxygen intake and HRV in RC in healthy adults. These findings show that HRV is an effective method for determining RC when designing exercise intensity training. It is stated that the increase in HF energy observed when RC is exceeded may be a result of the mechanical effect of the increased respiratory frequency on the heart (Cottin et al., 2006). Cassirame et al., (2015) showed a strong correlation between RC with HRV (r=0.92) and speed (r=0.91) during a field test in skiers. Contrary to these results, Cottin et al., (2007) found no difference in HRV and RC workload in healthy adults. Cottin et al., (2006), stated that the ventilator thresholds could be evaluated in terms of heart rate variability when examining trained participants on a cycle ergometer. Comparatively, in the current study HF continued to decline dramatically up to the first respiratory threshold and continued to rise, albeit low, between the first and second respiratory threshold. Therefore, for AT, it can be estimated as the point at which the decline of HF stops from the beginning of the exercise. With increasing breath rate, HF continues to recover more rapidly after the RC point.

Previous studies have indicated that HF beats in low-to-moderate intensity exercises and HF reacts in the opposite way, while in high-intensity exercises, LF decreases while HF increases (Perini et al., 1990, 1993; Hautala et al., 2003; Pichon et al., 2004; Povea et al., 2005), in contrast to some studies, reported an increase in low-to-moderate-intensity exercise and a decrease in high-intensity exercise (Radaelli et al., 1996; Tulppo et al., 1996). LF can be considered as an indicator of sympathetic nervous system activation (Camm et al., 1996). In our study, the change in LFnu value was found to be statistically significant within and between the threshold regions ($p<0.001$). This made us think that as the test gradually became more difficult, the regions where the differences in the LFnu value change were significant may be the threshold regions. This result is consistent with another study (Sarmiento et al., 2013; Lewis et al., 2007). Neufeld et al., (2019) stated that training between anaerobic and respiratory threshold regions in a study that lasted 8 weeks with 13 triathletes could be beneficial in terms of increasing the metabolic threshold value. Nakamura et al., (2015) stated in their study with futsal athletes that LnRMSSD values for ultra-short-term HRV can be useful in evaluating the effects of training.

It was observed that the HRV values measured as 30 seconds at the end of the test were not sufficient for recovery. MeanRR continued to decline significantly after the end of testing. It is recommended that the HRV record for recovery be longer in future studies.

There are some limitations in the current study that future research should consider. First, all participants were men in the current study therefore our results can be meaningful for only healthy men population. Secondly, the effect of gender differences was not evaluated since the performance groups were divided according to performance and there could be performance differences depending on gender (Augustsson et al., 2009; Cheuvront et al., 2005). The lack of controlled breathing conditions may also be a limitation in HRV measurements. Finally, not all HRV parameters were evaluated. Only variables frequently used in time-domain and frequency-domain variables were evaluated. For future studies, trained athletes, different genders, and additionally using different HRV parameters are recommended.

In conclusion, using a gas analyzer during cardiovascular exercise testing, HRV values (MeanRR, SDNN, RMSSD, LFnu) determined at seven stages continue to decrease from the beginning. A rest period of 30 seconds (passive rest) immediately after completing the exercise does not seem to be sufficient for recovery. According to the results of this study, it can be considered that the sympathetic nervous system activity (LFnu) exhibits a more pronounced appearance at threshold zones.

Conflict of interests: The authors state that there is no conflict of interest.

Authors' Contribution: Study design TA-RA, Data collection TA-RG, Statistical analysis TA-RA, Manuscript Preparation TA-RA-RG.

Information on Ethics Committee Permission Committee: Eskişehir Osmangazi University research ethics committee
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